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A High Efficiency Fast Neutron Detector

R.A. AUGUST, G.W. PHILLIPS AND J.H. CUTCHIN*

Condensed Matter and Radiation Sciences Division

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This report researches a concept for a high efficiency detector of fast neutrons (several MeV), using solid state charged particle detectors overlaid with thick disks (~mm) of ^{238}U. Experiments ~~at NRL~~ show a significant count rate in our mock-up when exposed to a fast neutron flux, but it appears insensitive to the slow/thermal neutron flux. Our preliminary results indicate a system with an efficiency on the order of at least 5% could be developed.

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EXECUTIVE SUMMARY

We are investigating the possibility of building a high efficiency detector of fast neutrons (several MeV). The concept uses solid state charged particle detectors overlaid with thick disks (~mm) of ^{238}U which has a neutron induced fission threshold at about 1.5 MeV. The vast majority of primary fission fragments will not be able to escape from the disks and be detected due to their short range. However, the highly energetic and prolific (charged particles, neutrons and γ-rays) nature of the fission reaction leads to secondary nuclear reactions and fission product decay particles. In particular, many of the electrons from β-decay of the fission products will be energetic enough to escape the ^{238}U disks. We hypothesize that this will increase the usable thickness of fissionable material by boosting the probability of a signal in the charged particle detector resulting from a fission in the disk. Experiments at NRL (Naval Research Laboratory) using 1 mm thick ^{238}U disks backed by silicon charged particle detectors show a significant count rate increase when exposed to a neutron flux. These events correlate well with the fast neutron flux but appear insensitive to the slow/thermal neutron flux. These preliminary results indicate a system with an efficiency on the order of at least 5% could be developed.

A HIGH EFFICIENCY FAST NEUTRO! DETECTOR

I. Introduction

A typical high efficiency fast neutron detector first thermalizes the neutron by multiple scattering in a hydrogenous material, then detects the thermal neutron in a proportional counter. All spectroscopic information is lost in the thermalization process, as is all information about the direction from which the neutron was incident upon the detector. These detectors typically have efficiencies of at least a few % for neutrons with energies in the MeV range (fast neutrons). Typical fast neutron spectrometry techniques, such as neutron time of flight, proton recoil telescopes, etc., suffer from efficiencies that are many orders of magnitude below this. Spectrometers using ^{10}B doped scintillators have been developed[1] that achieve efficiencies in the few % range, however, the energy resolution is rather poor being 55% to 33% fwhm in the range from 0.5 to 5.7 MeV.

The fast neutron detection approach we are studying skips the multiple collision process of thermalization and absorbs all of the neutron energy in one step via the fission reaction. There are a fair number of heavy elements that have relatively high fast neutron induced fission cross sections. In particular,

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^{238}U has fission cross sections for fast neutrons in the range of a barn (1 b = $10^{-24}cm^2$).

A problem is immediately obvious when the nature of the fission reaction is considered. When a fast neutron (a few MeV) induces a fission of ^{238}U, several hundred MeV of energy is released. Most of this energy is divided between two fission fragments. The rest is given to an average of three or more neutrons and released as γ-rays. This neutron multiplicity more or less eliminates this systems usefulness as a neutron spectrometer.

It does not eliminate the possibility of using it as a threshold detector for a yes/no discrimination between fast and slow neutrons. The reaction threshold for neutron induced fission of ^{238}U is at about 1.5 MeV. At this point the fission cross section rises sharply by a factor of 1000. This barrier will effectively discriminate between fast and slow neutrons. This discrimination would be further enhanced if a detector exploiting this reaction is also shielded by a thin layer of plastic heavily doped with ^{10}B (or some other thermal neutron shield), one would then greatly attenuate any thermal neutrons present without seriously affecting the fast neutron flux one was trying to measure.

Passive variations of this idea have been done[2] in the past by backing a fissionable foil with a film to record the tracks left by the fission products then counting the tracks after etching the film. Also, active fission fragment detectors have been around for some time[3]. These detectors use only very thin deposits of fissionable material so that the short range (on the order of microns) primary fission fragments[4] will be able to escape from the fissionable material and be detected. This strongly limits the efficiencies for fast neutron detection that these detectors can achieve.

II. NRL Detector

The detector we are developing sandwiches together standard solid state charged particle detectors and thick disks of ^{238}U. In our preliminary work the actual thicknesses of the ^{238}U disks were 1 mm. This is far too thick for the charged particle detector to observe the vast majority of the fission fragments that occur in the disk. However, the highly energetic and prolific (charged particles, neutrons and γ-rays) nature of the fission reaction leads to secondary nuclear reactions and fission product decay particles. In particular, many of the electrons from β-decay of the fission products will be energetic enough to escape the ^{238}U disks.[5] We hypothesize that this will increase the usable thickness of fissionable material by boosting the probability of a signal in the charged particle detector resulting from a fission in the disk. Our experiments indicate that this is in fact the case.

When the disk/detector sandwich was exposed to a ^{252}Cf neutron source a significant increase in count-rate was seen in the charged particle detector. After accounting for the effects of neutrons on the solid state detector, the majority of this increase can only be accounted for as being the result of neutron induced events in the ^{238}U disk. Further experiments where the incident neutron flux was moderated and the source to detector geometry varied, indicated that the neutron induced events were due to the fast neutron component of the flux. Calculations using the results of our experiments indicate that about half of the neutron induced fissions in the ^{238}U disk result in a signal in the charged particle detector, confirming our original hypothesis.

Our results suggest that a prototype detector could be constructed using these disk/detector sandwiches. The detector construction is most easily explained in two parts. The first part consists of individual "telescope" components. This component is shown in Fig. 1.

The disk/detector sandwiches are arranged in telescope fashion. The ^{238}U disks are each 2 mm thick and have charged

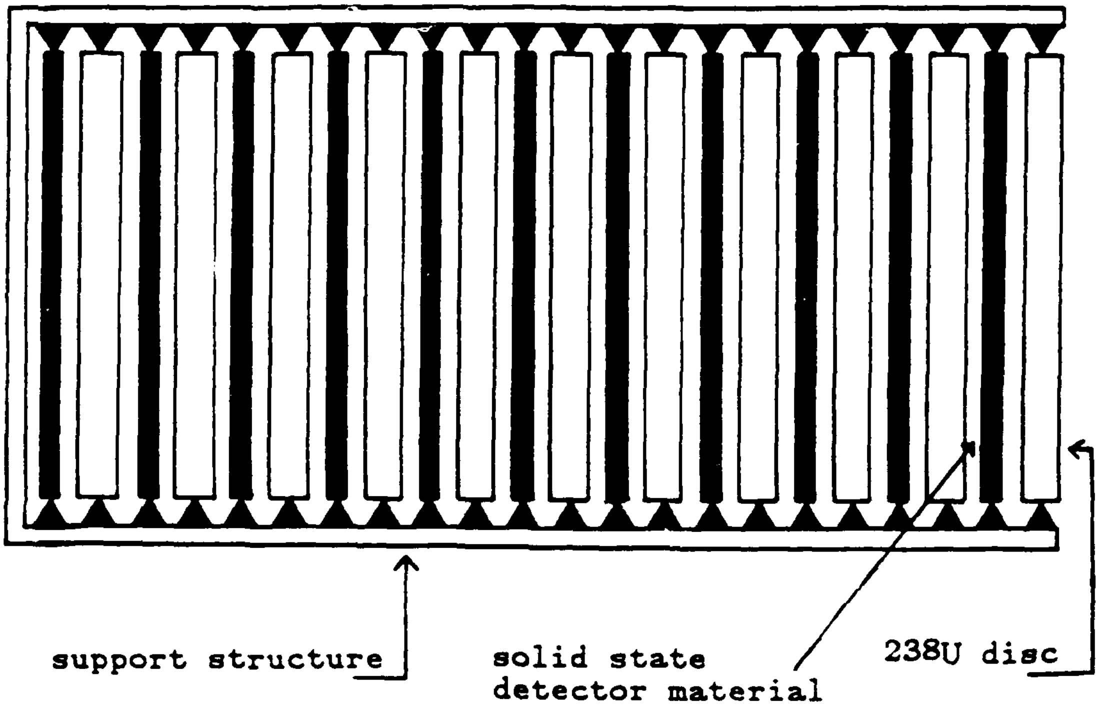

Fig. 1. Individual "telescope" component of the detector system shown in side cross section.

particle detector material sandwiched between each one. There are 11 total disk/detector sandwiches shown in Fig. 1. A 7-8 MeV neutron at normal incidence to one face of the "telescope" must travel through a total of 2.2 cm of ^{238}U, this results in a 10% probability that the neutron will induce a fission in one of the disks. As just mentioned, our experiments indicate that ~50% of these fission events will be detected in one of the charged particle detectors. Therefore, the overall probability that this 7-8 MeV neutron will be detected is ~5%. It should be noted that the overall thickness of ^{238}U (2.2 cm), the individual disk thickness (2 mm), the thickness of charged particle detector (not specified here), the spacing (if any) between the charged particle detector and ^{238}U disk, and the "telescope" support structure are not uniquely determined here. The 2 mm thickness for the ^{238}U disks was chosen because it allowed us to make detector performance estimates based on our current experiments. The actual optimum parameters for components is planned as the subject for future experimentation.

The second part of the detector construction involves arranging the individual "telescopes" in an array and surrounding the entire array with a passive thermal neutron shield (i.e. ^{10}B doped plastic). A 3x3 example of such an array is shown in Fig. 2 with the front face of the thermal shielding cut away so that the array of "telescopes" can be seen.

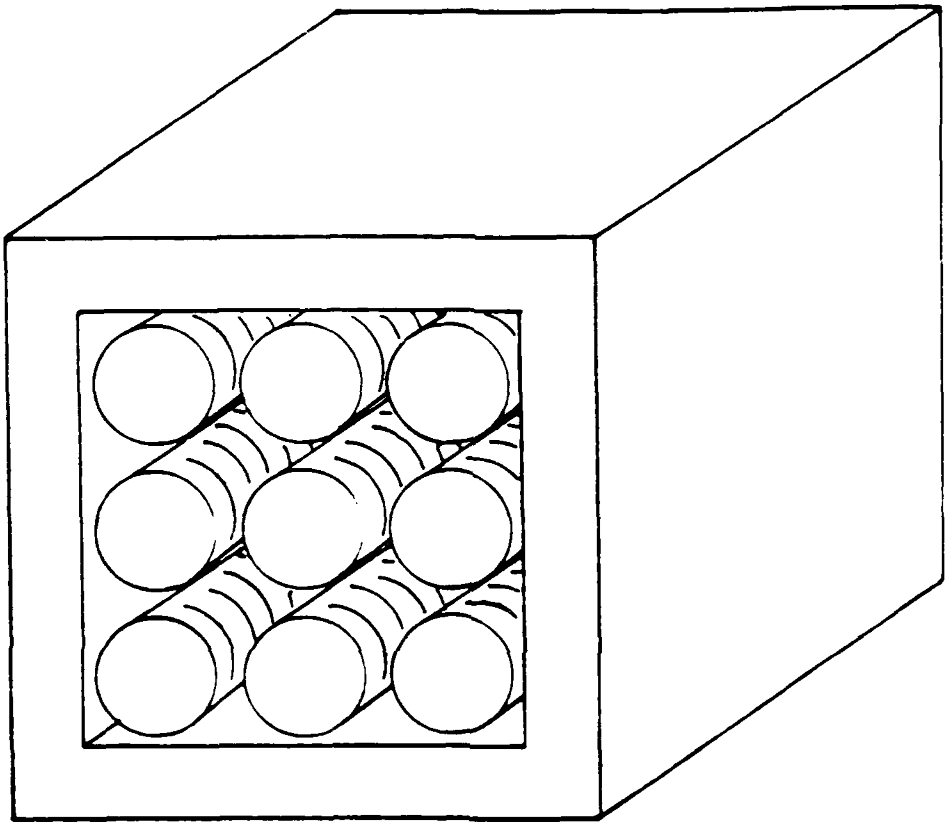

Fig. 2. Full detector system shown in perspective. The front thermal neutron shielding has been cut away showing the 3x3 array of individual "telescope" components.

Methods and materials for constructing passive thermal neutron shields are well known and can easily be made such that slow/thermal neutrons are strongly shielded against while fast neutrons are not seriously affected. Surrounding the detector array with such a shield will further suppress the systems sensitivity to slow/thermal neutrons without seriously affecting its fast neutron detection capabilities.

There are two advantages to having the "telescopes" in an array. The most obvious is that it increases the effective surface area of the detector. Perhaps less obvious is that since the neutron induced fission reaction is a one-step process and since each charged particle detector in the array is counting separately, there exists the possibility that by comparing relative count rates in the charged particle detectors one can ascertain from which direction the neutron flux is incident upon the detector array. Such directional information would be very limited in a small array like the one shown in Fig. 2. It is most likely that a much larger array would be needed to effectively exploit this possibility. To gauge the real possibilities for directional information we will have to take into account effects from fission neutrons and neutron scattering within the array.

III. Experimental Techniques

All experiments were performed at the Naval Research Laboratory in Washington, DC. The detectors used were transmission mounted silicon solid state charged particle detectors. The charged particle detector used in most experiments was 2000 microns thick, although some experiments were run with thinner detectors to gauge what effect this might have. The ^{238}U disks were obtained from 1 mm thick sheets that were available at NRL. Each 1 mm thick disk was cut to be the same size as the active area of the detector to which it was to be mounted. The disks were mounted right up against the detector face, with a disk mounted on both sides of the transmission mount detector. This was done so that the solid state detector would see a situation roughly approximating the telescope arrangement shown in Fig. 1.

Only one disk/detector assembly was tested at a time. The disk/detector assembly was put into an evacuated chamber and placed with one face parallel to a flat wall of the chamber at a distance of 1 cm. The wall of the chamber was 1/16 inch thick stainless steel. Two ^{252}Cf sources were used in these experiments, both had been previously calibrated to be 136 and 582 μCi. When a neutron source was in use it was placed outside the vacuum chamber normal to the center of disk/detector assembly. The distance between the neutron source and the disk/detector assembly was varied between 2 and 6 inches. When we wanted to moderate the neutron source, 1/2 inch thick, 2 feet x 2 feet polyethylene sheets were placed on the outside of the vacuum chamber between the neutron source and the disk/detector assembly.

Standard nuclear electronics were used and included a solid state detector power supply, preamplifier, spectroscopy amplifier, and electronic pulser for calibration. The data were collected on a Nuclear Data ND66 multichannel analyzer with its own ADC. An $^{241}A_m$ source was used as the calibration source for the charged particle detectors.

All experiments were performed following the same method. After setting up the disk/detector assembly in the vacuum chamber, a background spectrum was taken. This gave a spectrum of the natural background of the ^{238}U disks which is dominated by α particle decay. The neutron source (and polyethylene sheets if being used) was then put in place and a spectrum collected. The evacuated chamber was then opened and the disks removed. The charged particle detector was then replaced in the chamber without the disks and a spectrum was collected. This was done to check for the effects of the neutron flux on the charged particle detector. The neutron source was then removed and a spectrum was collected to check for any additional sources of background (none were found).

The detection events due to neutron induced events in the ^{238}U disks were then determined by comparing the summed counts in the spectrum taken when both the ^{238}U disks and neutron source were present with the other spectra taken. All spectra were taken for a length of time that assured a statistical accuracy of no worse than 0.5%. In actual practice this could vary anywhere between 20 minutes and several hours depending on the parameters of the actual set-up in use at the particular time.

Many experimental parameters were varied: amplifier gain, low energy discriminator level, neutron source, amount (if any) of polyethylene for neutron flux moderation, disk/detector to neutron source distance, geometry of the local environment, and thickness of the charged particle detector. After each variation spectra were taken following the experimental method just described.

Some of the variations just mentioned require further explanation. When experimenting with neutrons there is always concern that neutron scattering in the local environment can bias the results. To check for this the environment around the experimental set-up was varied by moving objects and moving the set-up itself. The polyethylene moderator was used to help determine if the neutron induced events in the disks were indeed due to the fast neutron component of the incident neutron flux, or if there was a significant contribution due to the slow/thermal components of the flux. A low energy discriminator level was set on the signal from the solid state detector in order to keep the experiments from being distorted by low energy noise. The thickness of the solid state detector was varied to help determine that the effects being seen were due to charges particles from the ^{238}U disks being stopped in the charged particle detector rather than being due to energy deposited by γ-rays passing through the charged particle detector.

IV. Experimental results

After a series of initial tests the amplifier gain was set to 8 MeV full scale and the lower level discriminator was set at 600 keV for the duration of these experiments. This discriminator setting was somewhat higher than was absolutely necessary, but we felt that it was more important to insure a clean spectrum in these tests than to try and maximize event detection efficiency.

The first spectrum to be taken was a ^{238}U disk background when no source was present. The disk/detector background count rate (summed over the entire spectrum) was 584.6 ± 0.4 counts/second. The ^{238}U that was available was not of a high isotopic purity (although it had been depleted of it's ^{235}U content) and thus this count rate is more than an order of magnitude higher than one would expect using purities that are currently commercially available.

The high background count rate forced us to use the larger neutron source and place it 2.5 inches from the detector when taking neutron spectra in order to obtain good counting statistics. Although spectra were taken with the neutron source further away they required longer counting times and produced results with less statistical accuracy. However, they were consistent with the reported 2.5 inch results. In future experiments we plan to use disks that are isotopically pure and expect that the disk background counts will then not dominate our spectra.

When spectra were taken with the strong neutron source 2.5 inches from the detector the count rate (summed over the entire spectrum) represented a 6.2 $\pm$ 0.1 % increase over the background counting rate. This is clearly a significant increase. Spectra that were collected in the presence of the neutron source but without the ^{238}U disks showed a count rate that was 3.2 $\pm$ 0.4 % of the background counting rate. Comparing this with the result obtained when the disks were present shows that 3.0 $\pm$ 0.4 % of the increase in the count rate in the solid state detectors can only be due to neutron induced events in the ^{238}U disks. This corresponds to a count rate of 17.5 $\pm$ 2.3 counts per second in the charged particle detector. Fig. 3 shows one of the spectra

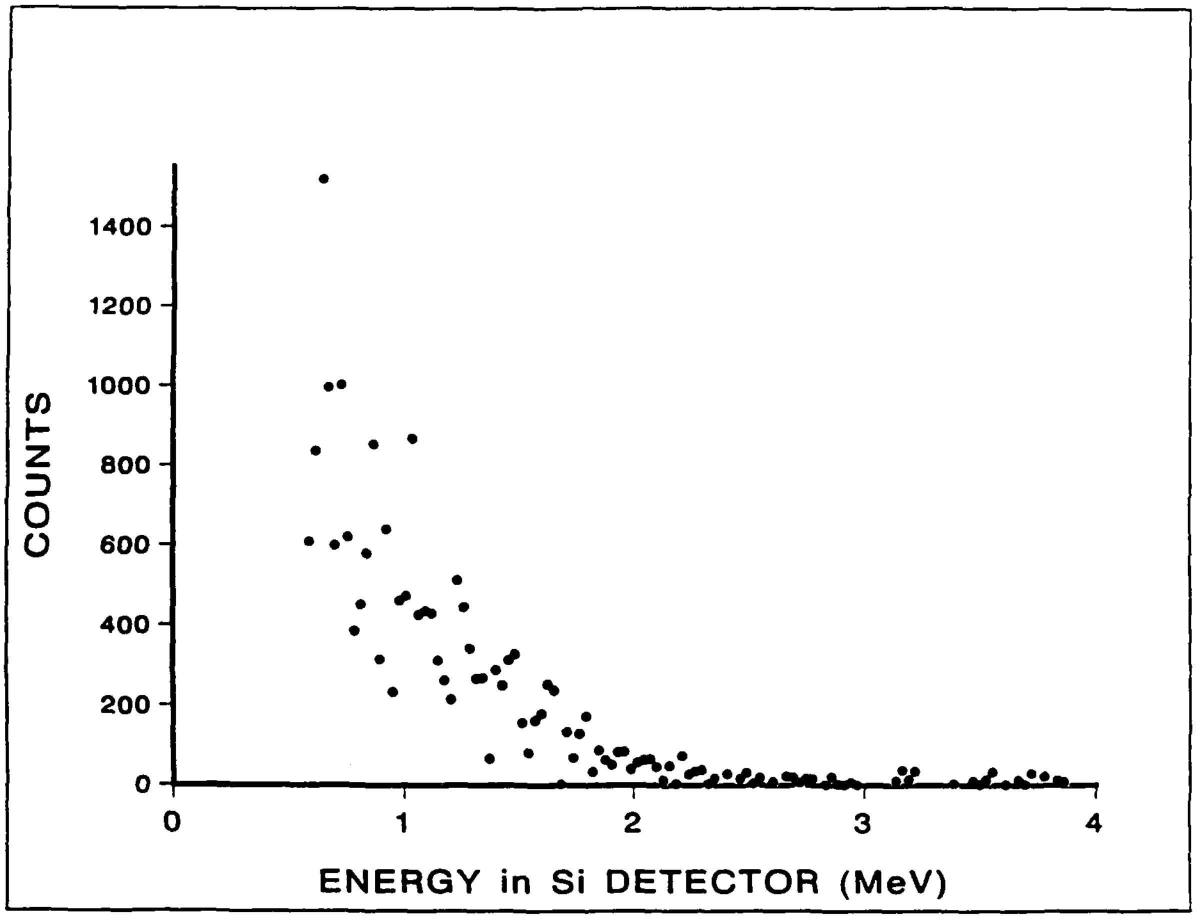

Fig. 3. Spectrum of counts in the charged particle detector resulting from neutron induced events in the ^{238}U disks.

of counts resulting from neutron induced events in the ^{238}U disks; this is a spectrum taken with the disks in and the neutron source present, minus spectra that were taken of the disk background and of the events due to neutron interactions in the charged particle detector.

During these experiments the charged particle detectors were periodically checked with the ^{241}Am source to look for possible effects from neutron damage. We found no evidence during the course of these experiments that the neutrons were adversely effecting the performance of the charged particle detectors. As explained in the previous section, the environment around the experimental set-up was varied; every time this was done the entire set of experiments were repeated. Using this method we found no evidence that neutron scattering in the environment was biasing our results.

To confirm that the interactions we have seen in the ^{238}U disks are indeed due to fast rather than slow/thermal neutrons, the experiments were repeated with polyethylene sheets between the neutron source and the disk/detector. Two total thicknesses of polyethylene were tested, 1/2 inch and 1 inch. With the 1/2 inch sheet the bare source count rate increase of 3.0 ± 0.4 % over background was reduced to 2.0 ± 0.4 %. With the 1 inch sheet present this was reduced to 0.7 ± 0.4 %. The spectral composition of neutrons emitted by ^{252}Cf is well known.[6] We used this to see if our results were consistent with published data concerning the moderation of fast neutrons.[7,8] Comparison showed that the behavior we should expect from the fast neutron component of a ^{252}Cf flux passing through our polyethylene moderator is consistent with our experimental results. We did not, however, make any detailed calculations at this time.

We did not make a similar comparison for the expected behavior of the slow/thermal flux as this is a far more complex situation; the process of thermalization creates additional slow/thermal neutrons, also, the local scattering environment becomes critically important in such calculations. It seems highly unlikely that the slow/thermal flux would be varying exactly as we would expect the fast flux to vary, especially since we have already mentioned that our experiments were insensitive to variations in the local scattering environment. We therefore believe that the neutron induced events in the ^{238}U disks that we are seeing are due to fast neutron interactions in the disk, with little apparent contribution from slow/thermal neutrons.

We then took the 17.5 $\pm$ 2.3 counts per second in the charged particle detector that we found to be due to neutron induced events in the ^{238}U disks, and compared this number to the rate at which we expected neutron induced fissions to be occurring in the disks. We knew the dimensions of the source to disk/detector geometry, and as we have already mentioned, the ^{252}Cf neutron energy distribution is well known. Therefore, it is a fairly simple calculation to fold this distribution into the known cross section distribution for neutron induced fission[9] in ^{238}U, and to obtain a fast neutron induced fission rate in the discs. Comparing this to our count rate indicates that 45% of the neutron induced fissions in the ^{238}U disks result in a signal in the charged particle detector. An accurate estimate of the error on this event detection efficiency number would require complex neutron scattering calculations. However, we feel confident that this error is small enough to reliably state that the event detection efficiency for this disk/detector set-up is ~50%.

V. Conclusions

Our experiments have shown that when our system of two 1 mm thick ^{238}U disks sandwiching a solid state charged particle detector is exposed to a flux of neutrons, a significant count rate can be seen in the charged particle detector attributable to neutron induced events in the disks. Our experiments indicate that these neutron induced events are due to fast neutron induced fission of ^{238}U. The efficiency with which neutron induced events in the disks produce signals in the charged particle detector is calculated to be ~50%.

We can use this 50% event detection efficiency number to estimate an overall fast neutron detection efficiency for the prototype detector shown in Figs. 1 and 2. We will consider a flux of 7-8 MeV neutrons at normal incidence to the face of the detector array. A neutron from such a flux passing through the active area of the detector array will encounter a total thickness of ^{238}U of 2.2 cm, this corresponds to a fission probability of 10%. Combining this with the event detection efficiency results in a overall fast neutron detection efficiency of 5%.

In order to increase the overall fast neutron detection efficiency there is no reason that one cannot increase the number of disk/detector layers. Also, the optimum parameters (i.e. disk and detector thickness, etc.) for this system have not yet been researched, and it is reasonable to expect that once these are determined a more efficient system will be possible. We conclude that the fast neutron detector we have described will have an overall efficiency for the detection of fast neutrons that is at least 5% and possible greater, for neutron energies of 7-8 MeV. Also, this detector should be extremely insensitive to slow/thermal neutrons.

VI. Future Work

We are interested in continuing this work in order to determine the optimum parameters for this detector, and to construct an actual prototype. This work will use high isotopic purity ^{238}U disks of varying thicknesses. We will also consider other fast neutron fissionable isotopes other than ^{238}U. We also plan to optimize other parameters such as charged particle detector thicknesses, passive shielding types and thicknesses, and other relevant parameters. Different sources of neutrons, and possibly neutron flux monitors will be used. Also, detailed neutron multiple scattering and absorption calculations will aid in the interpretation of our results.

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